

# THE SLUGGS SURVEY: A CATALOG OF OVER 4000 GLOBULAR CLUSTER RADIAL VELOCITIES IN 27 NEARBY EARLY-TYPE GALAXIES

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## ABSTRACT

Here we present positions and radial velocities for over 4000 globular clusters (GCs) in 27 nearby early-type galaxies from the SLUGGS survey. The SLUGGS survey is designed to be representative of elliptical and lenticular galaxies in the stellar mass range  $10 < \log M_*/M_\odot < 11.7$ . The data have been obtained over many years, mostly using the very stable multi-object spectrograph DEIMOS on the Keck II 10m telescope. Radial velocities are measured using the calcium triplet lines with a velocity accuracy of  $\pm 10$ -15 km/s. We use phase space diagrams (i.e. velocity–position diagrams) to identify contaminants such as foreground stars and background galaxies, and to show that the contribution of GCs from neighboring galaxies is generally insignificant. Likely ultra-compact dwarfs are tabulated separately. We find that the mean velocity of the GC system is close to that of the host galaxy systemic velocity, indicating that the GC system is in overall dynamical equilibrium within the galaxy potential. We also find that the GC system velocity dispersion scales with host galaxy stellar mass in a similar manner to the Faber-Jackson relation for the stellar velocity dispersion. Publication of these GC radial velocity catalogs should enable further studies in many areas, such as GC system substructure, kinematics, and host galaxy mass measurements.

*Keywords:* catalogs — surveys — galaxies: star clusters

## 1. INTRODUCTION

Radial velocities for globular clusters (GCs) beyond the Local Group were first published in the 1980s (Hesser et al. 1986; Huchra & Brodie 1987; Mould et al. 1987). Although these studies typically had individual GC velocity uncertainties of  $\geq 50 \text{ km s}^{-1}$ , they quickly showed the benefit of spectroscopically confirming GC candidates. For example, several of the brightest GC candidates around M87 from the imaging study of Strom et al. (1981) were shown to be background galaxies by Huchra & Brodie (1984).

As well as confirming that candidates from imaging are indeed bona fide GCs, radial velocities were employed to probe GC kinematics relative to the host galaxy (Hesser et al. 1986), investigate the velocity dispersion profile in the galaxy halo (Mould et al. 1987) and derive the enclosed mass to large radii (Huchra & Brodie 1987).

Globular cluster radial velocity studies have tended to focus on a small number of nearby massive early-type galaxies with rich GC systems, e.g. NGC 1316 (Richtler et al. 2014), NGC 1399 (Schuberth et al. 2010), NGC 3311 (Richtler et al. 2011; Misgeld et al. 2011), NGC 5128 (Beasley et al. 2008; Woodley et al. 2010), NGC 4472 (M49, Zepf et al. 2000; Cote et al. 2003), NGC 4486 (M87, Cote et al. 2001; Strader et al. 2011), NGC 4594 (M104, Bridges et al. 2007; Dowell et al. 2014), NGC 4636 (Schuberth et al. 2012). The number of GCs studied in a given system and the typical velocity uncertainty have improved since the earlier studies of the 1980s and 1990s. However, very few lower mass early-type galaxies had been studied by the mid 2000s.

The dual aims of the SLUGGS survey (Brodie et al. 2014) are to collect high quality GC and galaxy starlight spectra for a representative sample of early-type galaxies over a wide range of stellar mass (i.e.  $10 < \log M_*/M_\odot < 11.7$ ). The galaxy starlight spectra are used to probe the kinematics and metallicity of the host galaxy (see Brodie et al. 2014 for details) and have been reported elsewhere in the literature (see [www.sluggs.swin.edu.au](http://www.sluggs.swin.edu.au)). Over the last decade we have obtained over 4000 GC radial velocities associated with the 25 main galaxies, and ‘bonus’ galaxies, of the survey. Results have been published on a continuous basis over the years. This includes GC kinematics of individual galaxies (NGC 1407, Romanowsky et al. 2009; NGC 4494, Foster et al. 2011; NGC 4473, Alabi et al. 2015; NGC 4649, Pota et al. 2015), interacting galaxies (NGC 3607 and NGC 3608, Kartha et al. 2016), and a sample of a dozen galaxies (Pota et al. 2013). We have also used GC kinematics to derive

mass models of the host galaxy, thereby exploring its dark matter content (Napolitano et al. 2014; Pota et al. 2015; Alabi et al. 2016).

In the next section we summarise the SLUGGS early-type galaxy sample and the observational setup used. We then discuss the removal of potential contaminants and present the final GC radial velocity catalogs.

## 2. THE HOST GALAXY SAMPLE AND OBSERVATIONS

Our sample consists of GC systems associated with 25 early-type galaxies from the SLUGGS survey plus two of the three bonus galaxies (NGC 3607 and NGC 5866) that were observed with the same setup. Table 1 lists the 27 galaxies and some relevant properties, such as their distance, stellar mass, effective radius, morphology, environment, systemic velocity, stellar velocity dispersion within 1 kpc, and position (J2000 coordinates). Most of these properties are taken from Brodie et al. (2014), which also lists other properties of the galaxies.

We have obtained wide-field multi-filter imaging of the SLUGGS galaxies using the Subaru telescope under  $\leq 1$  arcsec seeing conditions. This is supplemented by HST and CFHT imaging. Publications presenting the imaging analysis of SLUGGS galaxies include NGC 1407 (Romanowsky et al. 2009), NGC 4365 (Blom et al. 2012), NGC 4278 (Usher et al. 2013), NGC 720, 1023 and 2768 (Kartha et al. 2014), NGC 1023 (Forbes et al. 2014), NGC 3115 (Jennings et al. 2014), and NGC 3607 and 3608 (Kartha et al. 2016). We plan to publish an imaging analysis of the GC systems of the remaining SLUGGS galaxies in due course.

Spectroscopic observations of GC candidates were obtained over the last decade using the DEIMOS spectrograph (Faber et al. 2003) on the Keck II 10m telescope. The DEIMOS instrument is used in multi-slit mode with each slit mask covering an area of  $\sim 16 \times 5 \text{ arcmin}^2$ . With a flexure compensation system, DEIMOS is a very stable instrument and ideal for obtaining red spectra of objects over a wide field-of-view. For the SLUGGS survey, we use the 1200 lines per mm grating, the OG550 filter, slit width of 1 arcsec and a central wavelength of  $7800\text{\AA}$ . This gives 50-100 spectra per mask around the calcium triplet (CaT) feature covering a wavelength range of  $\sim 6500\text{\AA}$  to  $9000\text{\AA}$ . Each mask targets either GC candidates or locations near the galaxy center in order to obtain spectra of the underlying galaxy starlight. Globular clusters are selected to cover the full range of expected colors but have a bias towards the brighter objects in a given GC system (in order to maximise the

signal-to-noise). Our setup has a spectral resolution of  $\sim 1.5\text{\AA}$  (FWHM). Observations were obtained under see-

ing conditions of typically  $\leq 1$  arcsec.

**Table 1.** SLUGGS Galaxy Properties

Galaxy (NGC)	Dist. (Mpc)	$\log M_*$ ( $M_\odot$ )	$R_e$ (arcsec)	Type	Env.	$V_{sys}$ (km/s)	$\sigma_{kpc}$ (km/s)	(R.A.) (deg.)	(Dec.) (deg.)
720	26.9	11.27	29.1	E5	F	1745	227	28.252077	-13.738653
821	23.4	11.00	43.2	E6	F	1718	193	32.088083	10.994917
1023	11.1	10.99	48.0	S0	G	602	183	40.100042	39.063285
1400	26.8	11.08	25.6	E1/S0	G	558	236	54.878483	-18.688070
1407	26.8	11.60	93.4	E0	G	1779	252	55.049417	-18.580111
2768	21.8	11.21	60.3	E6/S0	G	1353	206	137.906250	60.037222
2974	20.9	10.93	30.2	E4/S0	F	1887	231	145.638667	-3.699139
3115	9.4	10.93	36.5	S0	F	663	248	151.308250	-7.718583
3377	10.9	10.50	45.4	E5-6	G	690	135	161.926380	13.985916
3607	22.2	11.39	48.2	S0	G	942	229	169.227665	18.051756
3608	22.3	11.03	42.9	E1-2	G	1226	179	169.245632	18.148684
4111	14.6	10.52	10.1	S0	G	792	161	181.763052	43.065720
4278	15.6	10.95	28.3	E1-2	G	620	228	185.028434	29.280756
4365	23.1	11.51	77.8	E3	G	1243	253	186.117852	7.3176728
4374	18.5	11.51	139.0	E1	C	1017	284	186.265597	12.886983
4459	16.0	10.98	48.3	S0	C	1192	170	187.250037	13.978373
4473	15.2	10.96	30.2	E5	C	2260	189	187.453628	13.429359
4474	15.5	10.23	17.0	S0	C	1611	88	187.473113	14.068589
4486	16.7	11.62	86.6	E0/cD	C	1284	307	187.705930	12.391123
4494	16.6	11.02	52.5	E1-2	G	1342	157	187.850433	25.775252
4526	16.4	11.26	32.4	S0	C	617	233	188.512856	7.6995240
4564	15.9	10.58	14.8	E6	C	1155	153	189.112428	11.439283
4649	16.5	11.60	79.2	E2/S0	C	1110	308	190.916564	11.552706
4697	12.5	11.15	95.8	E6	G	1252	180	192.149491	-5.8007419
5846	24.2	11.46	89.8	E0-1/S0	G	1712	231	226.622017	1.6056250
5866	14.9	10.83	23.4	S0	G	755	163	226.622912	55.763213
7457	12.9	10.13	34.1	S0	F	844	74	345.249726	30.144941

NOTE—Distance, morphology, environment, galaxy systemic velocity and velocity dispersion within 1 kpc are taken from Brodie et al. (2014). Stellar masses and effective radii are from Forbes et al. (2016). Note that  $V_{sys}$  for NGC 4474 was reported incorrectly in Brodie et al. and has been corrected here. The position of each galaxy centre is taken from the NASA Extragalactic Database.

The spectra are reduced using the spec2d data reduction pipeline (Cooper et al. 2012) which produces sky-subtracted, wavelength calibrated spectra. We use FXCOR (Tonry & Davies 1979) within IRAF, along with 13 stellar template spectra (observed with DEIMOS in the same setup but in long slit mode), to determine the radial velocity of each object. Velocity errors are the

quadrature combination of the FXCOR error and the standard deviation from the 13 stellar templates (which cover a range of metallicity and spectral type), which give a minimum measurement uncertainty of  $\pm 3 \text{ km s}^{-1}$ . We visually check each spectrum and require that at least two of the three CaT lines (8498Å, 8542Å, 8662Å) and H $\alpha$  (if included in the redshifted spectrum) are

present. A small percentage of the spectra are ‘marginal’ in the sense that we can not be sure about the identification of the lines (e.g. due to low S/N or poor sky subtraction). In these cases we take a conservative approach and do not include them in our confirmed GC catalogs (nor those of confirmed contaminants). Radial velocities are corrected to heliocentric velocities. Our tests of repeatability (i.e. from observing the same objects on different nights) indicates a systematic rms velocity uncertainty of  $\pm 10\text{--}15$  km/s (Pota et al. 2013, 2015).

### 3. BACKGROUND GALAXIES AND FOREGROUND STARS

Our initial GC candidate selection is largely based on ground-based imaging which will include some contaminants, i.e. both compact background galaxies and foreground stars. By examining phase space diagrams, i.e. the radial velocity vs galactocentric radius of the GC candidates (see the Appendix for such diagrams of each galaxy’s GC system), it is fairly straight forward to identify and remove background galaxies on the basis of their high velocities i.e.  $V > 3000$  km s $^{-1}$  (from either absorption or emission lines).

For most GC systems, the GCs are also well separated in velocity from the most extreme Milky Way stars, which generally have velocities within  $\pm 300$  km s $^{-1}$  (although some rare examples of very high velocity halo stars do exist; Brown et al. 2010). For the half dozen GC systems that may overlap in velocity with Milky Way stars, one can assume that the GC velocities are distributed symmetrically about the galaxy’s systemic velocity and use those GCs with higher than systemic velocity to define the distribution (see for example Usher et al. 2013). Extending that velocity distribution to velocities less than the galaxy’s systemic velocity, gives an indication of likely foreground star contaminants. An additional clue comes from the object’s galactocentric radius since the velocity dispersion of a GC system tends to decrease with radius; very few GC system phase diagrams have objects with  $V < 300$  km s $^{-1}$  at large radii.

Our final GC catalogs are thus our best effort at removing foreground stars and background galaxies but a small number of such contaminants may still be present. We do not attempt to remove any GCs associated with substructures within a GC system that may have been acquired from a merger/accretion event (see Alabi et al. 2016 for a discussion of this issue). The exception to this is NGC 4365 ( $V_{sys} = 1243$  km s $^{-1}$ ) for which GCs deemed to be associated with the interacting galaxy NGC 4342 ( $V_{sys} = 761$  km s $^{-1}$ ) have been removed (see Blom et al. 2014 for details). Table 2 lists foreground star and background galaxy contaminants (we do not quote actual recession

velocities for background galaxies as we only applied absorption line templates) identified for each SLUGGS galaxy (excluding NGC 4486, 4494 and 4649).

**Table 2.** Contaminants

ID	R.A. (deg.)	Dec. (deg.)	V (km/s)	$V_e$ (km/s)
NGC720_star1	28.166625	-13.666556	158	7
NGC720_star2	28.221083	-13.783722	6	5
...	...	...	...	...
NGC720_gal1	28.231667	-13.773028	99	99

NOTE—ID, Right Ascension and Declination (J2000), heliocentric radial velocity and velocity uncertainty. Velocities and velocity uncertainties of 99 denote no measured value. The full table is published online.

### 4. NEIGHBORING GALAXIES

A neighboring galaxy may also possess its own GC system which, if close in projection on the sky and in radial velocity, could be confused with that of the primary SLUGGS galaxy. For most of the SLUGGS galaxies, there is no nearby neighbor of substantial size and hence rich GC system. The main exception is the Leo II galaxy group. Here we have used HST and Subaru imaging along with the spectroscopically-confirmed GCs to remove any GCs likely associated with the dwarf galaxy NGC 3605 and assign the bulk of GCs to either NGC 3607 or NGC 3608 (Kantha et al. 2016). GCs identified as being associated with NGC 4459 may in principle belong to the very rich GC system of nearby NGC 4486 (M87). For NGC 4459, the bulk of its GCs lie within  $\sim 2$  galaxy effective radii but some half a dozen objects lie at large radii and may actually belong to M87. For NGC 4278 we include here, the 3 GCs that may be associated with NGC 4283 as identified by Usher et al. (2013). For NGC 1407 and NGC 1400, the galaxies are separated by over 1000 km s $^{-1}$  in velocity and 10 arcminutes on the sky, so it is straight forward to assign their relative GC systems. Otherwise the neighboring galaxies tend to be low mass galaxies and/or located at large projected galactocentric radii. Table 3 lists potential neighbor galaxies that are projected within 12 arcmins, differ by less than 1000 km/s in systemic velocity and are less than 4 magnitudes different from the primary SLUGGS galaxy. From our phase-space diagrams (see the Appendix) the contribution from neighboring galaxies’ GC systems appear to be small and we have not attempted

to remove any such GCs from the SLUGGS galaxy GC system.

**Table 3.** Neighbor galaxies

Galaxy (NGC)	Neighbor galaxy	$\Delta V_{sys}$ (km/s)	$\Delta R$ (arcmin)
3377	NGC 3377A	117	7.0
3607	NGC 3605	281	2.8
3607	NGC 3608	-284	5.9
3608	NGC 3607	284	5.9
3608	NGC 3605	565	8.4
4111	NGC 4117	-142	8.6
4111	UGC 07094	13	11.6
4278	NGC 4283	-436	3.5
4278	NGC 4286	-24	8.6
4365	NGC 4366	-33	5.1
4365	NGC 4370	461	10.1
4374	NGC 4387	452	10.3
4459	NGC 4468	283	8.6
4473	NGC 4479	1384	11.4
4474	NGC 4468	702	5.6
4486	NGC 4478	-65	8.7
4649	NGC 4647	-299	2.6
5846	NGC 5846A	-489	0.6
5846	NGC 5845	240	7.3
5846	NGC 5850	-844	10.3
7457	UGC 12311	-76	7.8

NOTE—Neighbor galaxies that lie within 12 arcmins on the sky,  $<1000$  km/s in systemic velocity difference and  $<4$  magnitudes difference, systemic velocity of SLUGGS galaxy minus that of the neighbor and projected distance on the sky.

## 5. ULTRA-COMPACT DWARFS

As well as removing background galaxies and foreground stars from our GC object lists, we have attempted to remove an additional source of ‘contamination’ by Ultra-Compact Dwarfs (UCDs). UCDs appear very similar to GCs in ground-based imaging, and lack a standard definition. Working definitions have included half light sizes greater than 10 pc and/or luminosities brighter than  $M_V \sim -11$  (i.e. on the order of  $\omega$  Cen in our Galaxy). In order to measure sizes for objects around SLUGGS galaxies (which have typical distances of 20 Mpc) HST imaging is generally required, and not always available for our GC sample. Here we have taken

a conservative approach of excluding the small number of GC-like objects with an equivalent luminosity of  $M_i \leq -12$  (this roughly corresponds to  $M_V < -11$  and masses greater than two million solar masses); thus our GC object lists may still include a small number of low luminosity UCDs with sizes greater than 10 pc (see Forbes et al. 2013). We tabulate the objects we identify as UCDs in Table 4 for the galaxies NGC 821, 1023, 1407, 2768, 4365, 4494 and 4649. We note that Table 4 includes the 3 objects identified as UCDs around NGC 4494 by Foster et al. (2011) even though they have luminosities of  $M_i \sim -11.8$ , which is slightly fainter than our limit. For a discussion of UCDs around NGC 4486 (M87) we refer the interested reader to Strader et al. (2011). We adopt a naming convention of NGCXXXX\_UCDXX, i.e. the galaxy NGC name and a sequence of identified ultra-compact dwarfs.

**Table 4.** Ultra-Compact Dwarf Radial Velocities

UCD ID	R.A.	Dec.	V	$V_e$	Rad
NGC821_UCD1	32.086091	10.990721	1705	6	0.28
NGC1023_UCD1	40.144680	39.090030	619	4	2.63
NGC1023_UCD2	40.115950	39.078000	338	3	1.15
NGC1407_UCD1	55.007179	-18.630067	2110	5	3.84
NGC1407_UCD2	55.067500	-18.481872	2164	5	5.98
NGC1407_UCD3	55.065921	-18.541622	1665	5	2.49
NGC1407_UCD4	55.058625	-18.641786	1482	5	3.74
NGC1407_UCD5	55.089904	-18.725344	1712	5	9.01
NGC1407_UCD6	54.861854	-18.688042	1995	6	12.5
NGC1407_UCD7	55.041750	-18.568922	1954	5	0.80
NGC1407_UCD8	54.963000	-18.485567	1621	35	7.51
NGC1407_UCD9	55.096717	-18.505539	1973	3	5.22
NGC1407_UCD10	55.017663	-18.562511	2509	4	2.09
NGC1407_UCD11	55.039700	-18.560778	1187	4	1.28
NGC2768_UCD1	137.903214	60.071148	1194	5	2.04
NGC4365_UCD1	186.096020	7.317350	1518	5	1.30
NGC4365_UCD2	186.062140	7.320480	800	5	3.32
NGC4365_UCD3	186.082990	7.300690	1446	5	2.31
NGC4365_UCD4	186.110750	7.319560	979	5	0.44
NGC4365_UCD5	186.148890	7.306630	1586	5	1.96
NGC4365_UCD6	186.086620	7.311630	898	5	1.89
NGC4365_UCD7	186.120030	7.366040	929	5	2.90
NGC4494_UCD1	187.856312	25.772158	1281	5	0.37
NGC4494_UCD2	187.852679	25.804469	1341	5	1.77
NGC4494_UCD3	187.863296	25.767058	1152	5	0.86

*Table 4 continued*

Table 4 (*continued*)

UCD ID	R.A.	Dec.	V	$V_e$	Rad
NGC4649_UCD1	190.950662	11.534806	826	3	2.27
NGC4649_UCD2	190.938146	11.589529	1275	4	2.55
NGC4649_UCD3	190.912098	11.576443	796	25	1.45
NGC4649_UCD4	190.700026	11.920495	1221	28	25.5
NGC4649_UCD5	190.913204	11.549560	1526	8	0.27
NGC4649_UCD6	191.042458	11.578678	1450	28	7.56
NGC4649_UCD7	190.735808	11.619961	1227	22	11.4
NGC4649_UCD8	190.788416	11.648972	1042	16	9.49

NOTE—Ultra-compact dwarf ID, Right Ascension and Declination (J2000), heliocentric radial velocity (km/s), velocity uncertainty (km/s) and galactocentric radius (arcmin).

## 6. GLOBULAR CLUSTER RADIAL VELOCITY CATALOGS

In Table 5 we present our GC radial velocity catalogs. Each catalog lists the globular cluster ID, its position, heliocentric radial velocity, velocity uncertainty and galactocentric radius (in arcminutes) for each SLUGGS galaxy. The position of each galaxy centre is given in Table 1. For object IDs we use a naming convention of NGCXXXX\_SXXX, i.e. the galaxy NGC name and a sequence of SLUGGS velocity-confirmed globular clusters. We do not include any GCs that we determined to have marginal (i.e. non secure) measurements of their velocity. The catalog for NGC 3115 includes GCs observed by Arnold et al. (2011) using Keck/LRIS and Magellan/IMACS as well as Keck/DEIMOS. For NGC 4649, the catalog includes GCs observed using Gemini/GMOS, MMT/Hectospec as well as Keck/DEIMOS as compiled by Pota et al. (2015). Our catalog for NGC 4486 includes GCs observed by the MMT/Hectospec, particularly at large galactocentric radii, as well as Keck /DEIMOS. See Strader et al. (2011) for details. Our Keck/DEIMOS observations of NGC 4365 were extended to include GCs around NGC 4342 which is separated by  $\sim 20$  arcmin and  $\sim 500$  km/s in velocity (Blom et al. 2014). Here we only include GCs associated with NGC 4365 and refer the reader to Blom et al. (2014) for the GCs associated with NGC 4342. When a GC has been observed multiple times, we list the average velocity value and average uncertainty (combining errors in quadrature). These new, updated catalogs presented in Table 5 supersede previous SLUGGS GC radial velocity catalogs (e.g. Usher et al. 2012; Pota et al. 2013).

Table 5. Globular Cluster Radial Velocities

NGC 720					
GC ID	R.A.	Dec.	V	$V_e$	Rad
NGC720_S1	28.165375	-13.732361	1794	11	5.07
NGC720_S2	28.217625	-13.731111	1805	10	2.06
NGC720_S3	28.165917	-13.715389	1772	11	5.21
...	...	...	...	...	..

NOTE—Globular cluster ID, Right Ascension and Declination (J2000), heliocentric radial velocity (km/s), velocity uncertainty (km/s), galactocentric radius (arcmin). The full table is published online.

In Table 6 we summarise our final GC radial velocity catalogs. We list the number of unique DEIMOS masks and the total integration time. Note these masks were usually of dual purpose, i.e. as well as GCs, we obtained spectra of the underlying galaxy starlight to probe host galaxy kinematics (Arnold et al. 2014; Foster et al. 2016) and metallicity (Pastorello et al. 2014). If the emphasis of a given mask was on obtaining starlight then the GC return rate may be lower than if we had dedicated the mask to GCs. Table 6 also lists the number of unique confirmed GCs – this excludes those objects determined to be marginal GCs, background galaxies, foreground stars and UCDs. For each GC system we calculate the error-weighted mean heliocentric velocity along with its uncertainty, and the velocity dispersion (the standard deviation of the distribution).

Table 6. GC system catalog properties

Galaxy (NGC)	Masks	Time (hr)	$N_{GC}$	$\langle V \rangle$ (km/s)	$\sigma$ (km/s)
720	5	10.65	65	1751	168
821	7	10.17	68	1743	161
1023	5	8.82	113	626	153
1400	4	7.61	68	605	131
1407	11	19.20	374	1771	238
2768	6	11.50	107	1328	160
2974	5	8.67	26	1860	128
3115	5	9.54	150	710	166
3377	5	11.66	126	682	106
3607	5 <sup>a</sup>	10.07 <sup>a</sup>	39	976	158

Table 6 continued

Table 6 (*continued*)

Galaxy (NGC)	Masks	Time (hr)	$N_{GC}$	$\langle V \rangle$ (km/s)	$\sigma$ (km/s)
3608	5	10.07	29	1195	165
4111	4	8.00	15	833	124
4278	6	9.92	269	638	191
4365	7	9.26	245	1218	223
4374	3	5.50	41	1171	334
4459	3	6.50	36	1172	137
4473	4	8.75	105	2273	130
4474	3	5.70	23	1613	56
4486	5	13.42	653	1324	380
4494	5	8.08	105	1342	92
4526	4	8.00	107	588	175
4564	3	4.50	26	1185	116
4649	4	6.67	423	1097	256
4697	3	5.30	90	1244	151
5846	7	10.47	211	1720	245
5866	1	1.00	20	747	127
7457	5	10.65	40	839	79

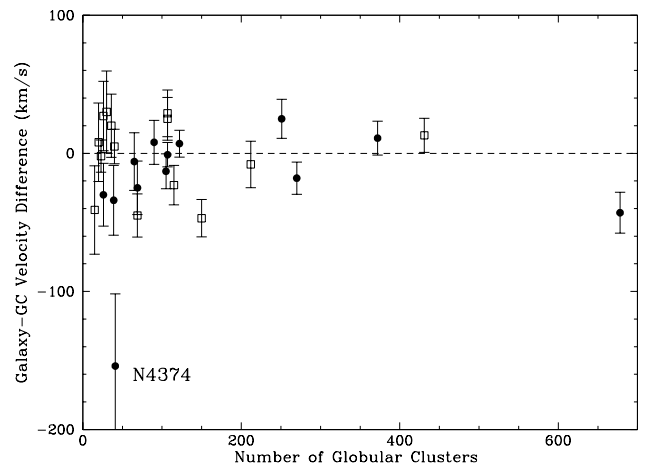
<sup>a</sup>NGC 3607 globular clusters were obtained from the NGC 3608 masks.

NOTE—Number of unique DEIMOS masks and total integration time, number of unique confirmed globular clusters, mean heliocentric velocity and the error on the mean, and the velocity dispersion of globular cluster system. Note that the final catalogs of NGC 3115, NGC 4649 and NGC 4486 include data from telescopes/instruments other than DEIMOS.

In Figure 1 we examine the difference between the mean velocity of the GC system with the galaxy systemic velocity as a function of the number of GCs observed. Each galaxy is coded by its Hubble type from Table 1. Most GC systems have a mean velocity that is similar to that of their host galaxy. The main outlier in our sample is NGC 4374 for which we have only 41 GCs, and so we suspect that this discrepancy is due to our limited and biased coverage of the GC system. There no obvious trend with Hubble type or number of GCs observed (beyond the expected larger scatter for smaller sample sizes). We conclude that, overall, our GC radial velocity datasets are representative of the GC system dynamics and that they are qualitatively consistent with being in dynamical equilibrium within the galaxy potential. Future work will investigate this issue in more detail and in particular whether substructure (e.g. due to a past merger) is present in these GC systems. For

example, in the case of a recent major merger, a ‘ringing effect’ is expected (A. Burkert 2016, priv. comm.) whereby GCs at large radii will deviate to positive and negative velocities as they settle into equilibrium.

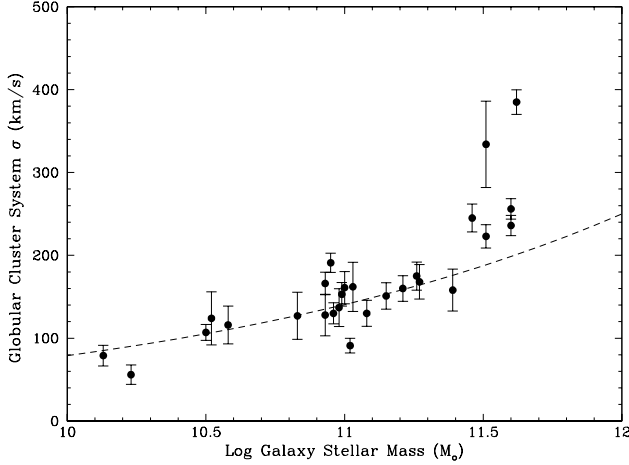
Early-type galaxies are well known to display a relationship between their luminosity (or stellar mass) and the velocity dispersion of their stars. This is commonly called the Faber-Jackson relation (Faber & Jackson 1976). For typical early-type galaxies the scaling is  $M_* \propto \sigma^4$ , but for the most massive galaxies the scaling steepens to an exponent of  $\sim 8$  (Kormendy & Bender 2013). In Figure 2 we show the relation between the velocity dispersion of the GC system and galaxy stellar mass. Stellar masses are calculated from the total  $3.6\mu\text{m}$  luminosity with an age dependent mass-to-light ratio (Forbes et al. 2016). A Faber-Jackson style  $\sigma^4$  relation is overplotted, showing that the GC system of typical early-type galaxies obeys a similar relation and that it steepens towards the more massive galaxies. For other kinematic scaling relations between GC systems and their host galaxies see Pota et al. (2013a,b).



**Figure 1.** Galaxy systemic velocity minus globular cluster system mean velocity vs number of GCs ( $N$ ) with radial velocities. Error bars represent globular cluster system velocity dispersion divided by  $\sqrt{N}$ . Symbols are coded by Hubble type (filled circles for ellipticals, and open squares for S0s and E/S0). The GC systems and their host galaxy have similar mean velocities, with the main outlier being NGC 4374. There is no strong trend with the number of GCs observed or Hubble type.

## 7. SUMMARY

After removing foreground stars, background galaxies and suspected ultra-compact dwarfs from our object lists, we present catalogs of over 4000 globular cluster (GC) radial velocities and positions for the SLUGGS early-type galaxies. Phase space diagrams for each



**Figure 2.** Galaxy stellar mass vs globular cluster system velocity dispersion. The dashed line is not a fit, but it shows a  $M_* \propto \sigma^4$  relation. The most massive galaxies have a steeper relation. Errors are globular cluster system velocity dispersion divided by  $\sqrt{N}$ , where  $N$  is the number of GCs. The galaxy with the largest error bar is NGC 4374.

galaxy indicate that contamination from nearby galaxies is low. We show that the mean velocity of the GC system is closely aligned with the systemic velocity of the host galaxy, and that the velocity dispersion of the GC system scales with host galaxy mass similar to the well-known Faber-Jackson relation. We hope that these data prove useful in future studies of GC systems. As new data are obtained we plan to make them available on the SLUGGS website <http://sluggs.swin.edu.au>

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*Facilities:* HST(ACS), Subaru(HSC),  
Keck(DEIMOS)

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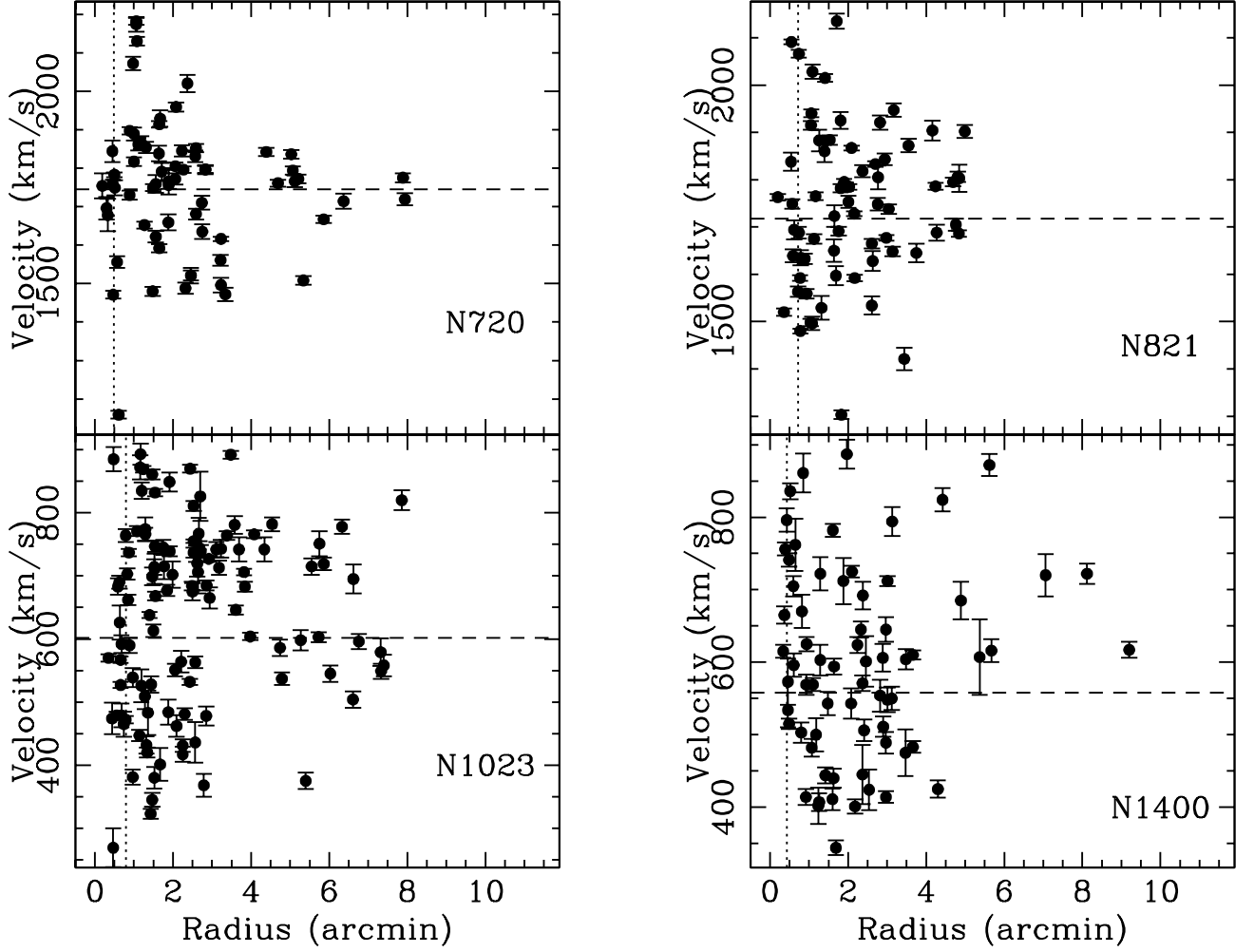
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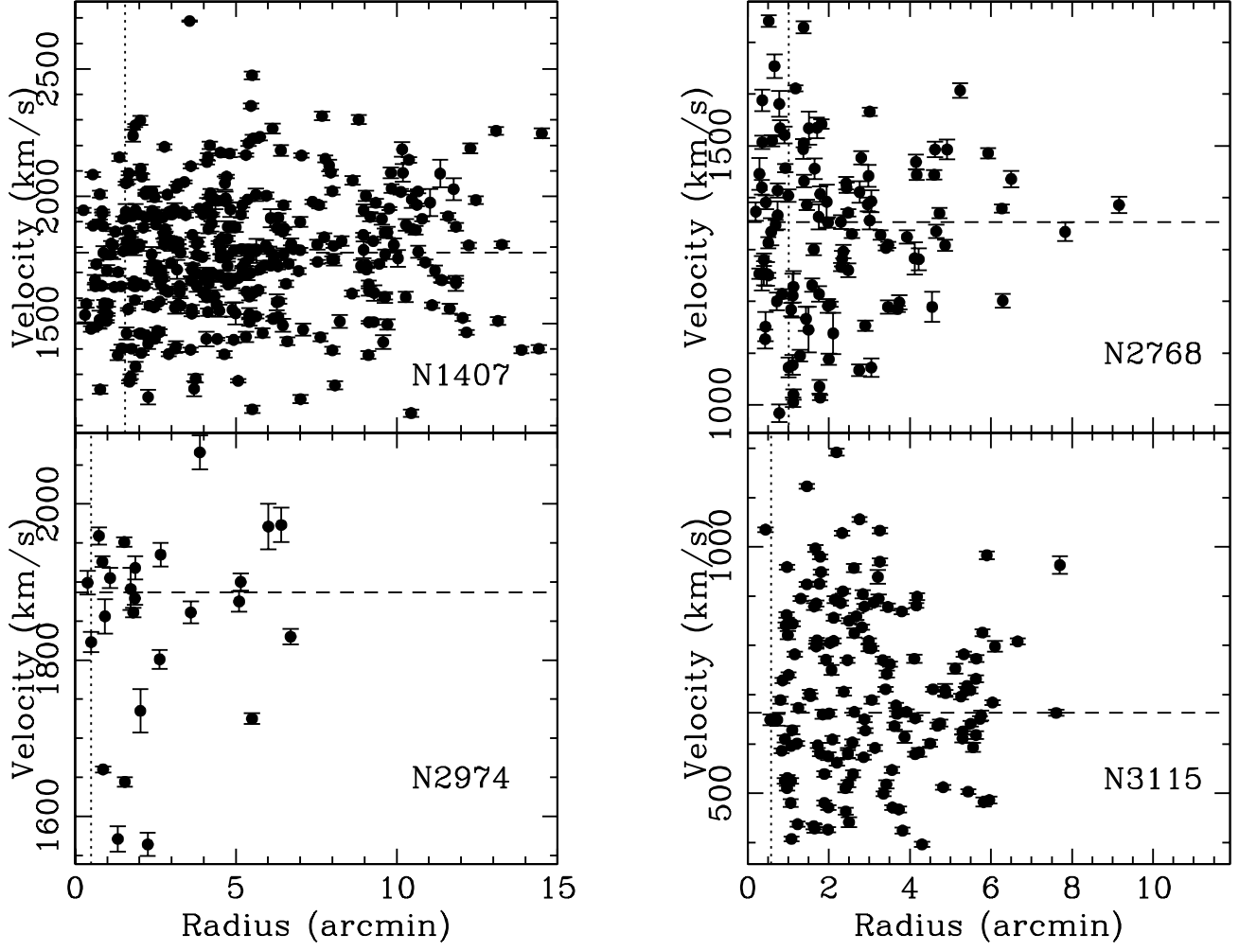
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## 9. APPENDIX

In Figures 3–9 we show the distributions of GCs in phase space, i.e. velocity vs projected galactocentric radius for individual host galaxies (see Alabi et al. 2016 for a summary plot stacked by galaxy mass). We also show the galaxy systemic velocity, effective radius and the location of neighbor galaxies (from Table 3). The GC systems generally have a velocity distribution that is symmetric about the galaxy systemic velocity, but there are some notable exceptions e.g. NGC 4374 as highlighted in Figure 1. These plots show that the contribution of GCs from the neighbor galaxies to the overall GC system of the primary SLUGGS galaxy is negligible.



**Figure 3.** Phase space diagram of GCs associated with NGC 720, NGC 821, NGC 1023 and NGC 1400. Small crosses indicate the location of neighbor galaxies as listed in Table 3. Ultra-compact dwarfs have been omitted from these diagrams. The horizontal dashed line indicates the systemic velocity of the host galaxy, and the vertical dotted line represents the effective radius of the host galaxy.



**Figure 4.** Phase space diagram of GCs associated with NGC 1407, NGC 2768, NGC 2974 and NGC 3115

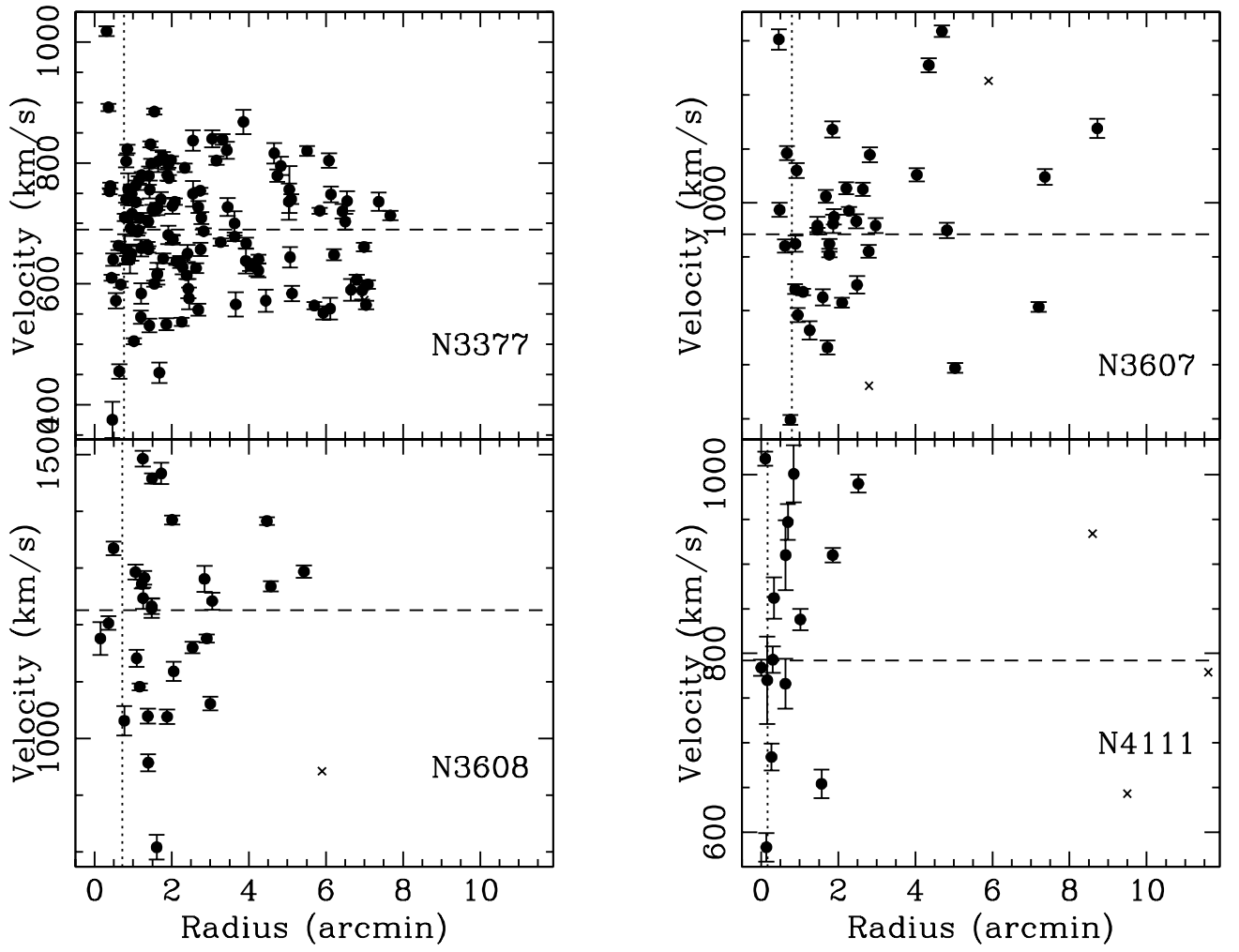
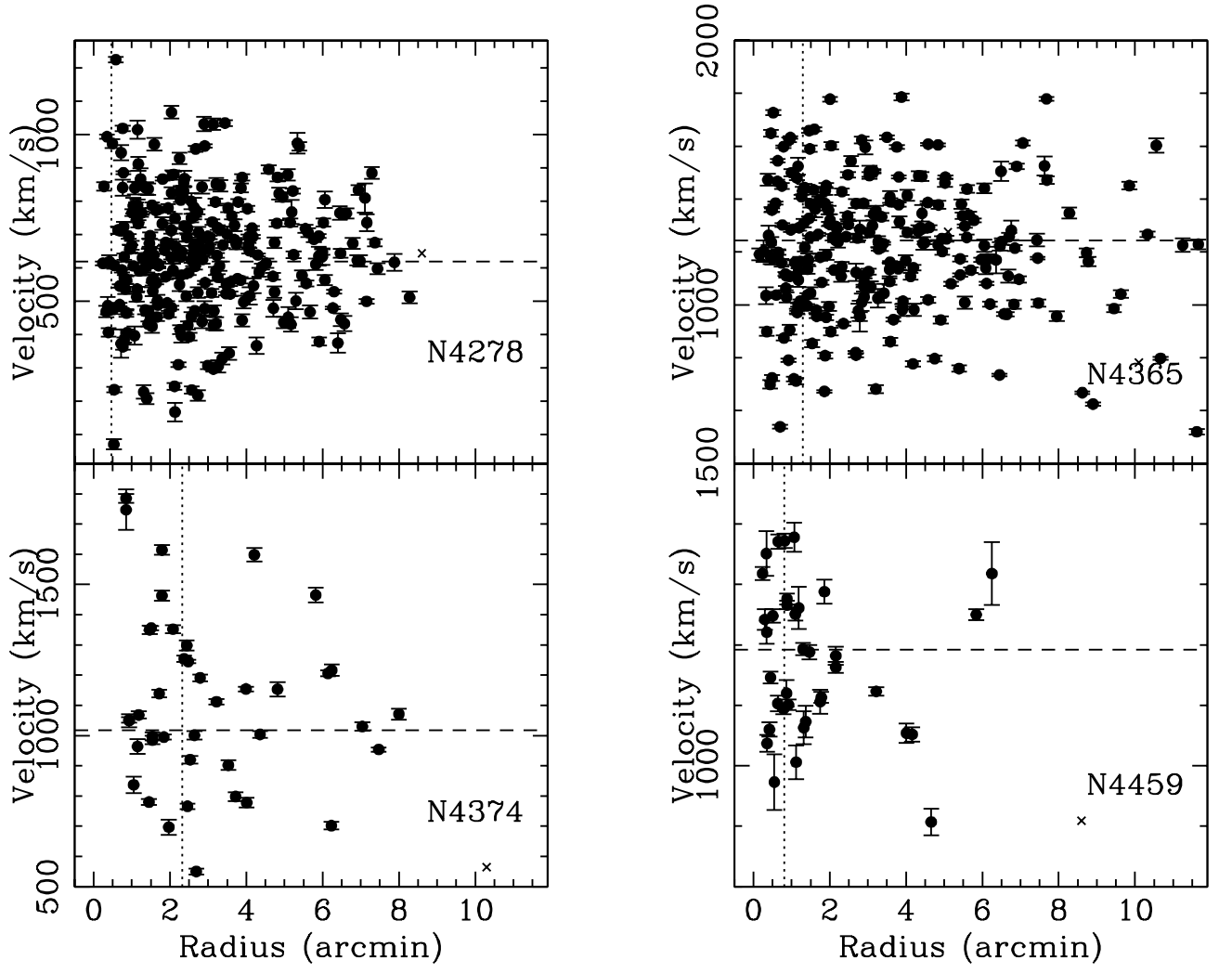


Figure 5. Phase space diagram of GCs associated with NGC 3377, NGC 3607, NGC 3608 and NGC 4111.



**Figure 6.** Phase space diagram of GCs associated with NGC 4278, NGC 4365, NGC 4374 and NGC 4459.

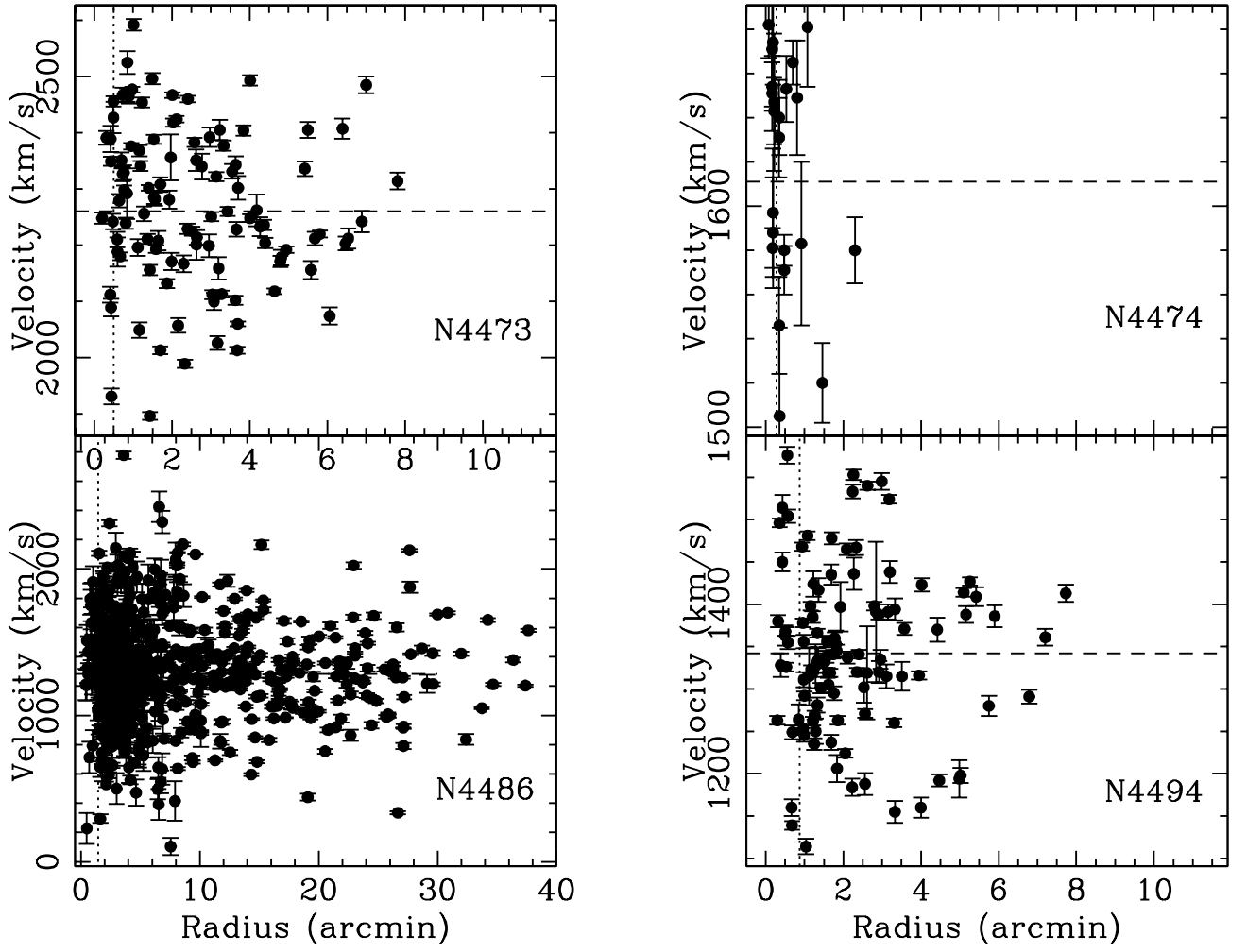


Figure 7. Phase space diagram of GCs associated with NGC 4473, NGC 4474, NGC 4486 and NGC 4494.

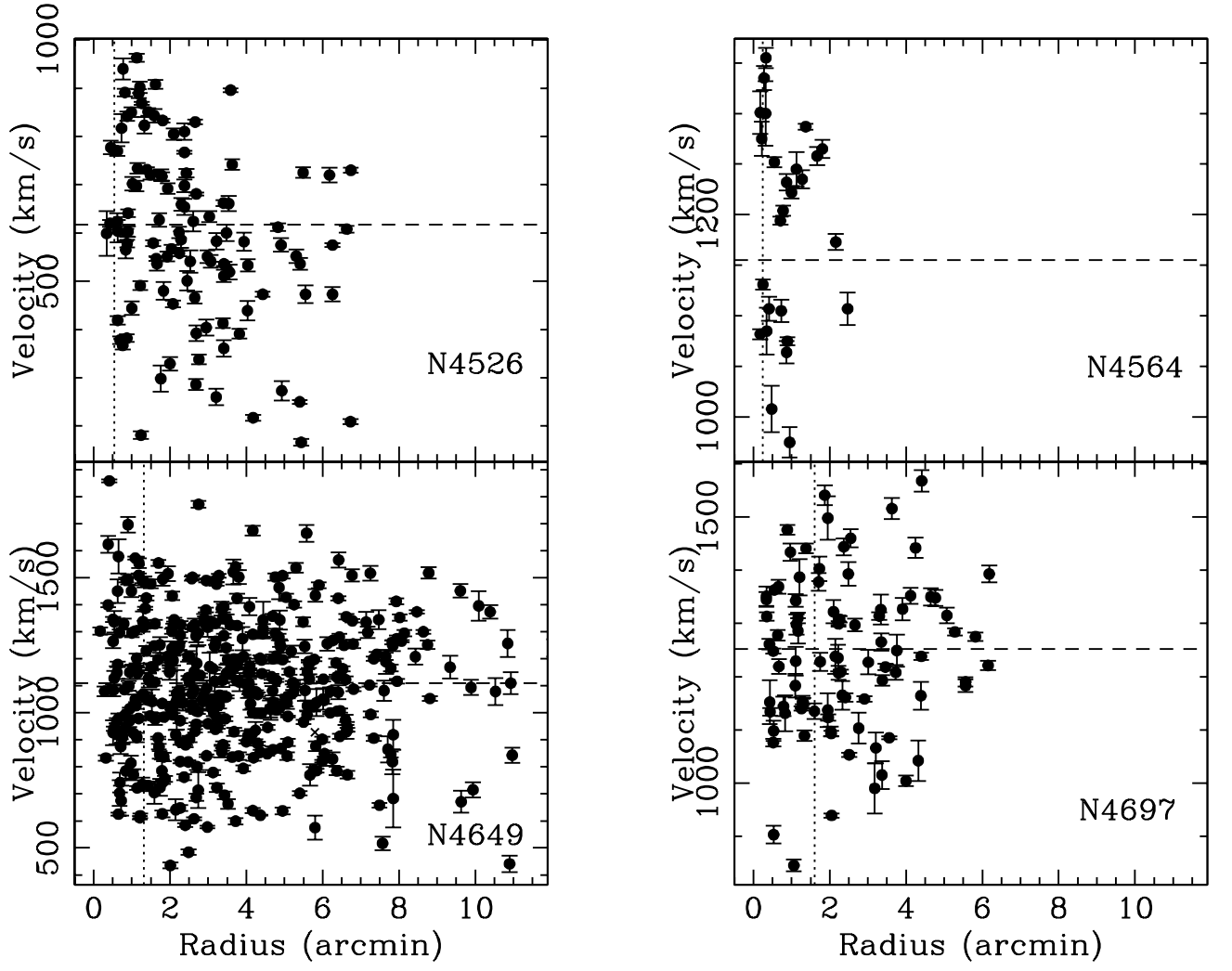


Figure 8. Phase space diagram of GCs associated with NGC 4526, NGC 4564, NGC 4649 and NGC 4697.

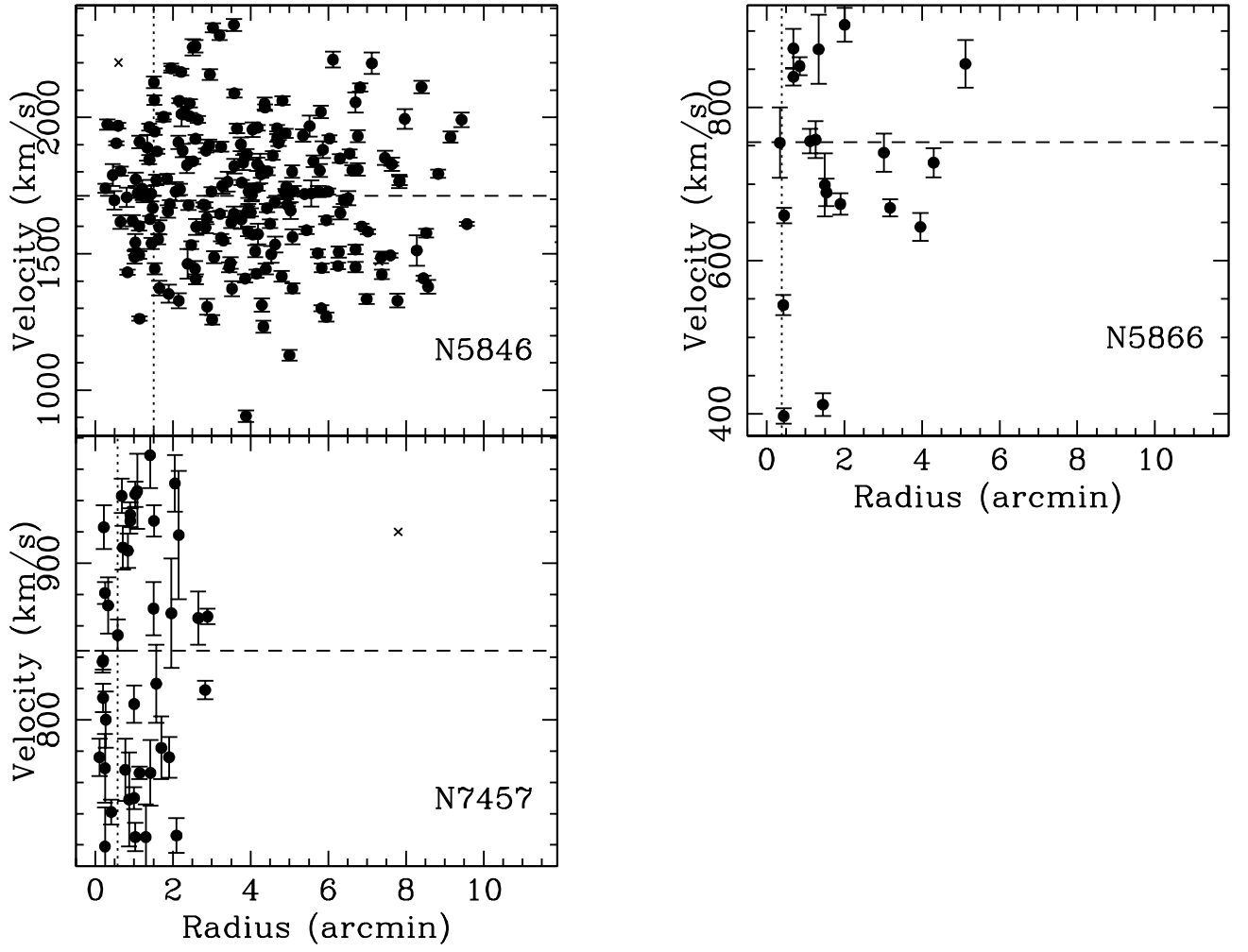


Figure 9. Phase space diagram of GCs associated with NGC 5846, NGC 5866 and NGC 7457.